An Explorative Study on International Collaboration and Its Role in Research Trajectory: Evidence from U.S.-China Collaboration in Nanotechnology

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***Abstract* -- The impacts of international collaboration on research performance have been extensively explored in the last two decades. Most research, however, focuses on quantity and citation-based indicators. Utilizing the turnover of keywords, this study develops a new method tracking the shift of the research stream and tests it within the context of U.S.-China collaboration in nanotechnology. The results find evidence in support of the linkage between the emergence of new research stream(s) of Chinese researchers in the event of U.S.-China collaboration. It also finds that the triggered research stream diffused further via extended coauthorship. Policy implications for both the U.S. and China S&T development are discussed in the end.**

***Keywords* -- U.S.-China collaboration, keywords analysis, knowledge spillover, nanotechnology**

I. INTRODUCTION

The last two decades have witnessed China's emergence as a scientific leader. China is the second most productive country in terms of knowledge creation, and the number of Chinese papers indexed in the Web of Science increased at an average annual growth rate of 20% between 2001 and 2006. According to EI Engineering Village, an engineering-oriented database, the number of Chinese papers increased from 18,600 to 65,100 during the same period, indicating an average annual growth rate of 50% [1]. Before hailing the rapid increase in the number of publications in China, one should bear in mind that knowledge production has been growing exponentially in numerous countries and disciplines. Taking that into account, China is still an outlier in terms of growth in scientific output. Continuing an upward trend in both scientific pursuits and the global share, from 1.4% in 1990 to 8.8% in 2006, China is unique among the seven most productive countries in scientific output (Figure 1).

China's astonishing publication activity is particularly reflected in the emerging field of nanotechnology. Measured by the number of nano-research articles, China is now the world's second largest producer of scientific research [2], [3], and [4].[1] In terms of citations, the visibility of Chinese nano research is also increasing over time [5]. China's growth in science and technology has aroused considerable interest among outside observers, and various reasons have been advanced to explain this phenomenon. Among them are the resources generated by China's fast-growing economic development, high levels of human capital, and technocratic policy push [6 and 7].

Except for the above three generally agreed-upon contextual factors, knowledge spillover associated with international collaboration is often presumed to be another salient reason for China's rapid development in nanotechnology. Until now, however, this causal relationship has only been assumed but not studied empirically. In an attempt to contribute to the body of empirical knowledge in this research area, this study develops a novel method for examining the role of U.S.-China collaboration in driving China's rapid accumulation of knowledge from the perspective of research content dynamics. The rest of the paper proceeds as follows: section 2 summarizes previous studies examining the impact of international collaboration; section 3 presents the main idea of this approach; section 4 uses this method and tests the impact of U.S.-China collaboration on the development of research streams; and section 5 discusses contributions, limitations, and policy implications and concludes with future research direction.

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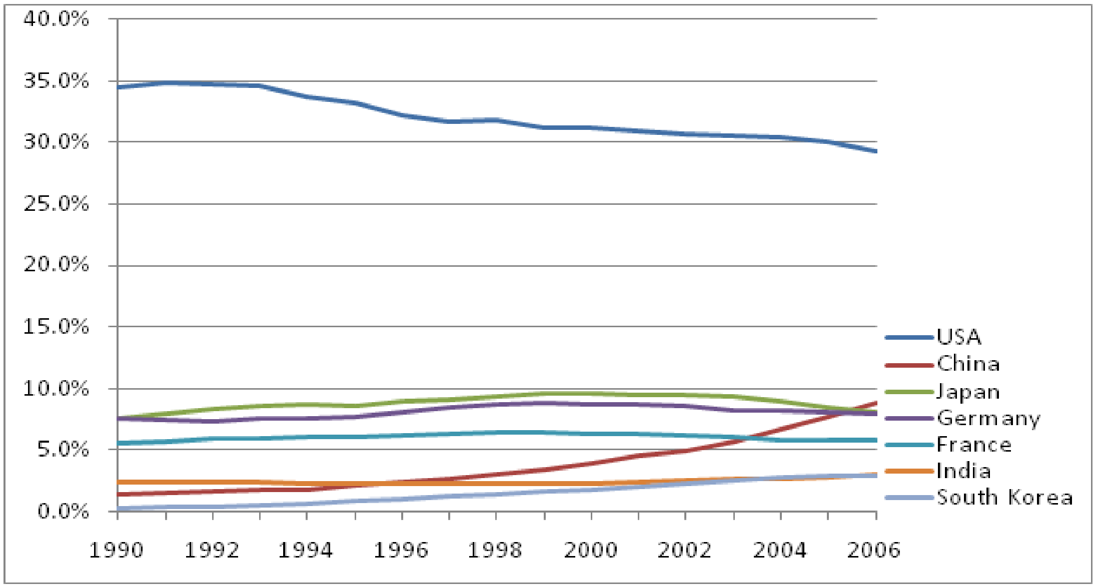
[1] Some studies argue that China publishes more academic papers on nanotechnology than any other country [39].

Figure 1: Publication Shares of the Seven Most Productive Countries



SOURCE: Calculated by the author based on SciSearch downloading at Fraunhofer ISI, Germany. Whole counting is used here.

II. LITERATURE REVIEW

Science is becoming increasingly global in the emerging knowledge economy. Studies consistently report dramatic increases in international collaboration over the last several decades [8, 9, and 10]. The European Commission [11] found that more than 740,000 international co-publications were indexed in the Thompson ISI in the period 1996–1999. Wagner [12] noted that 15% of global publications in 1998 alone were international collaborations. These numbers hold not only in the advanced economies [13, 11, and 14], but also in emerging scientific countries such as China, India, and South Korea [8, 15, 16, and 17]. This emergence of a "new invisible college" has not only the interest of social scientists but also has captured the attention of policy makers [18]. Indeed, realizing the benefits of monitoring and exploiting other countries' R&D investment, many countries are recognizing and championing joint international research [13].

The impact of international collaboration on research performance is not a new topic, having been extensively explored in prior research. In spite of the rich volume of results in the literature, the results are in disagreement. Since the seminal work of Katz and Martin [19], the amount of evidence supporting the positive *correlation* between collaboration and research performance has been accumulating. Narin and his colleagues [20] found that biomedical papers with international co-authors have a larger impact than both single-authored and nationally co-authored papers. Bordons and his co-authors [21] claimed that in Spanish biomedical publications, internationally co-authored articles were of higher quality and international collaborators more productive than their domestic counterparts. A recent study led by Barjak and Robinson [22] demonstrated the positive impact of international collaboration on the quantity and quality of a European Union research group. Other studies reported similar findings [14] and [23].

Conflicting evidence has been reported recently. For example, Leimu & Koricheva [24] found that internationally co-authored articles do not receive more citations than domestically co-authored papers in the field of ecology. In a comparative study, Duque and his colleagues [25] found that, in the context of developing countries, collaboration is not related to "any general increment in productivity." Findings in support of the trade-off effect of international collaboration on quantity and quality have also been reported. Using the panel publication data of 110 top U.S. universities, Adams *et al*. [26] argued that foreign collaboration among research institutes was positively correlated with citations but negatively correlated with productivity. In another study on one large European university, Carayol and Matt [27] reported no evidence of the impact of international collaboration on research productivity at the lab level.

Prior research, while insightful, confines the analyses on the impact of international collaboration to research productivity and research visibility, while its impact on the shift of research trajectory is largely ignored. This research seeks to address this gap by developing a new method for examining the radical change of research topics associated with international collaboration. This method is tested by three cases in the context of scientific collaboration between the U.S. and China. Case studies on the evolution of research streams suggest that U.S.-China collaboration influences the research trajectory of Chinese international collaborators, who, as the conduits of knowledge, disseminate it freely within the national boundaries of China.

III. HYPOTHESES

An unspoken norm in academia is that scientists actively push the research frontier within their capacity. Borrowing the notion of "creative destruction" from the entrepreneurship literature, scientists seek to push their knowledge boundaries forward, rendering existing knowledge obsolete. Assume that an international collaborator has a fixed knowledge stock K_i at the time t_i, denoted as $K_i \in [K_L, K_H]_{t_i}$. Then his increased knowledge stock at t_j can be denoted as ΔK, in which

$\forall\ j>i$: $\Delta K = K_j - K_i = [K_L, K_H]_{t_j} - [K_L, K_H]_{t_i} > 0$

On the other hand, if $t_j - t_i$ is close enough to 0, ΔK is expected to be marginally greater than zero, considering the bounded rationality of human beings. Applying this in the context of the research stream, a change in the research topics of each individual scientist would become incremental rather than radical within a short period.

It is highly unlikely that one researcher could reorient his main focus of research overnight; thus, I hypothesize that a radical discontinuous change, if any, is triggered by an external impetus such as knowledge spillover associated with interactive learning (co-authorship). Built on the extant research and the development trajectory of both the United States and China, I posit two hypotheses for testing:

H1: *The emergence of a new research stream for a Chinese international collaborator is related to the advent of collaborating with U.S. scholars.*

H2: *The new research stream triggered by U.S.-China collaboration is further diffused within China by extended co-authorship.*

If H1 is supported, it will provide evidence for a leader-follower pattern of U.S.-China collaboration and the impact of U.S.-China collaboration on research streams of Chinese scientists. Hypothesis 2 attempts to untangle the question of whether or not the new stream triggered by U.S.-China collaboration is picked up by Chinese international scholars and diffused to other Chinese domestic researchers. If H2 is supported, it will indicate an extended knowledge spillover from the U.S. to China via the knowledge conduit of Chinese international collaborators.

IV. METHOD

Stimulated by the idea of using "bibliometric fingerprints" for name disambiguation [28], a similar approach is developed to discern the emergence of the research stream, if any, of an individual scientist over time based on the dissimilarity of keywords in academic papers. This approach has two main goals: 1) to determine whether the emergence of a new research line was related to a case of international collaboration; and 2) to determine whether the new stream triggered by international collaboration diffused further to other Chinese domestic scholars.

In this study, keyword is used as a proxy indicator of research content. The unit of analysis is similarity in the focus of research of a pair of articles, measured by the research cohesion score (RCS), whose value is determined by the summation of shared keywords. Mathematically, the research cohesion score can be denoted as

$$\text{RCS}\ [i,j] = \sum_{i=n}^{i=1} \sum_{j=n}^{j=1} [A * K]_{n*m}$$

where

A is the collection of the publications of an individual scientist, $\mathbf{A} = \{a_1, a_2, \dots, a_n\}$

K is the set of selected keywords reported by **A**, and

$\mathbf{K} = \{k_1, k_2, \dots, k_m\}$.

Different from the algorithm proposed for the identification of authorship, no weighting is used here. However, to reduce the confounding clustering impact introduced by sharing common keywords, this study manually excluded terms such as "preparation," "particle," "synthesis," "investigation," and "characterization" from the selected keywords field.

It should also be noted that in using keywords to track the evolution of a research stream, one hurdle that must be overcome is to identify the *real standardized* nanotechnology keywords since no such field is ready for analysis. This challenge has been addressed, or at least reduced, by the following three sequential steps of cleaning: 1) automatic cleaning using VantagePoint, a text-mining software, by which fuzzy matching and thesauri were used to remove uninteresting stop words; 2) several rounds of manual keyword standardization and cleaning to consolidate certain nano term variations using regular expressions; and 3) validation from nanoscientist researchers on keyword "synonymies"—that is, different keywords and their variants denoting the same concept or topic in order to reduce the issue of substitution.

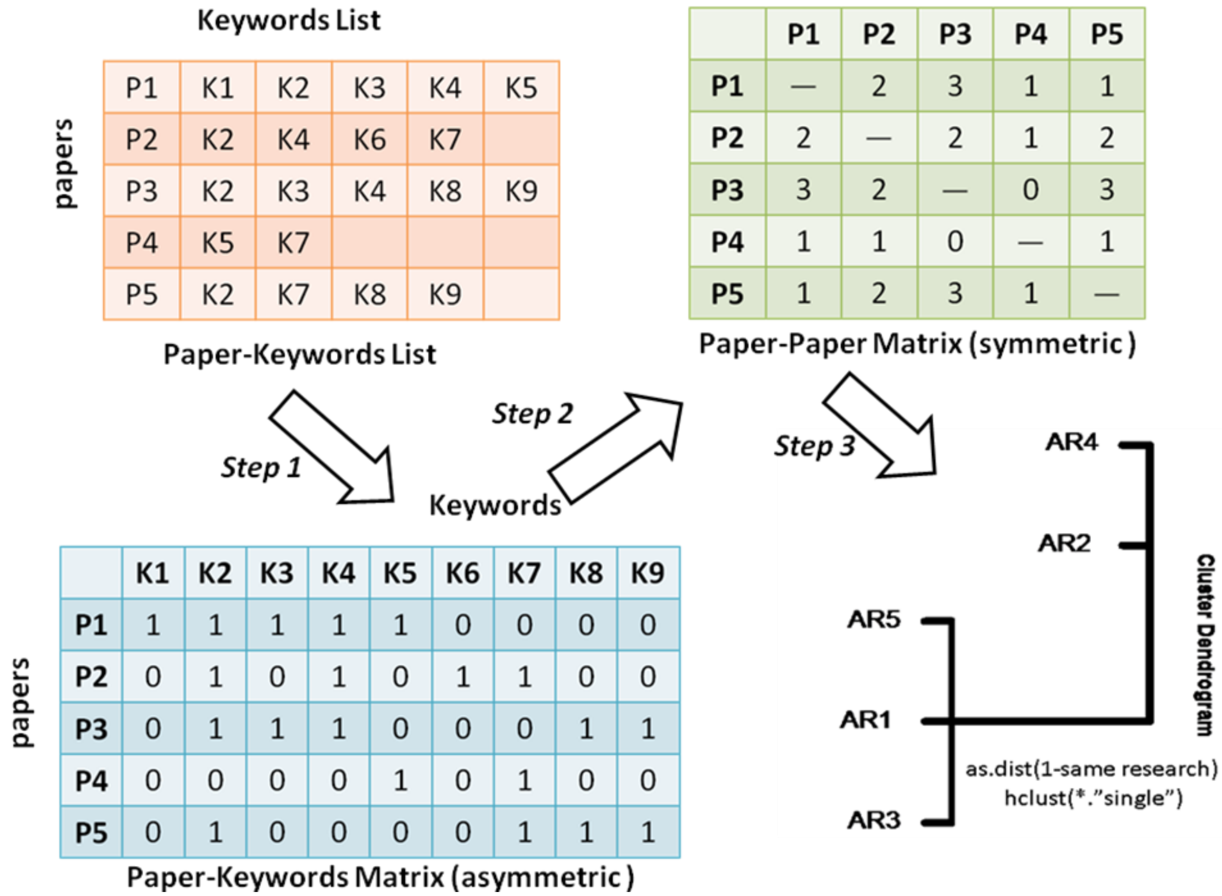
The process of analysis proceeds as follows. The set of publications associated with a targeted researcher was first extracted from the Chinese international collaborator dataset. The corpus of keywords was then obtained from a composite keywords field that included three sets of keywords offered by the author and structured by the journal and title phrases achieved by the natural language processing (*NLP*) function in text-mining software, respectively.[2] The generation of this field of composite keywords can be justified in two ways. For one thing, not every article contains either keywords reported by the author or keywords structured by the journal. In Chinese nanotechnology publications, the coverage of keywords (author's) and Keywords Plus are 65% and 90%, respectively. Secondly, my past experiences working on Chinese nano publication data suggest that the combination of the above two keyword fields with a title can best capture the research content of articles.

Once the standardization and selection of keywords were complete, a 2-D matrix of the paper title * selected keywords was created. The clustering function in the R program, which produces different groups, was used. So that the linkages of different articles written by individual authors could be visualized, the concept of an approximate structural equivalent (ASE) in social network analysis was also applied. Simply put, in a single-relation network, actors within a structurally equivalent cluster are more similar than those outside the cluster [29, 30, and 28]. Upon application of this notion to the identification of research continuity, two articles were considered approximately structurally equivalent if they were similar in the position of written keyword(s) in an article-keywords bipartite network [31]. Articles allocated to different clusters indicate different research lines.

Considering the incremental research shift within each researcher over time, transitivity is imposed using a hierarchical clustering with a single linkage. Thus, if the research cohesion score determined that AR_1 and AR_2 fit into the same research line and that AR_2 and AR_3 discussed the same research subject, then AR_1, AR_2, and AR_3 were aligned with the same research cluster even if AR_1 and AR_3 themselves had no shared keywords. This process was iterated via R program until all transitivity matches were completed. Figure 1 illustrates the process. For more details on this method, readers can refer to Tang & Walsh [28].

[2] They are Keywords (Author's) and Keywords Plus, shown in WoS data, and phrases extracted from the title.

Figure 1: Illustration of Identifying New Research Streams by Keywords Analysis



Source: Figure 1 is adapted from Zhang, Chen & Li [32].

Case Studies

The above hypotheses are tested for three Chinese nanoscientists and their research activity from the 1990 to 2006, which are extracted from a global nanotechnology dataset developed by the Georgia Tech researchers. For detailed discussion of this dataset, please refer to Porter *et al.* [33]. Considering the well-documented name ambiguity problem [28], this study extends tremendous effort to verify their publications by combining CV data, online searches, and verifications with researchers.

Two Chinese nanoscientists who are currently working in China are intentionally chosen to advance our understanding of the relationship of keyword turnover and international collaboration. The selection criteria are based on a balanced consideration of the following factors: 1) region—eastern China vs. western China; 2) university rank—elite university vs. non-elite university; and 3) age cohort—middle career researcher vs. senior researcher.

Case 1: Zu Xiao Tao

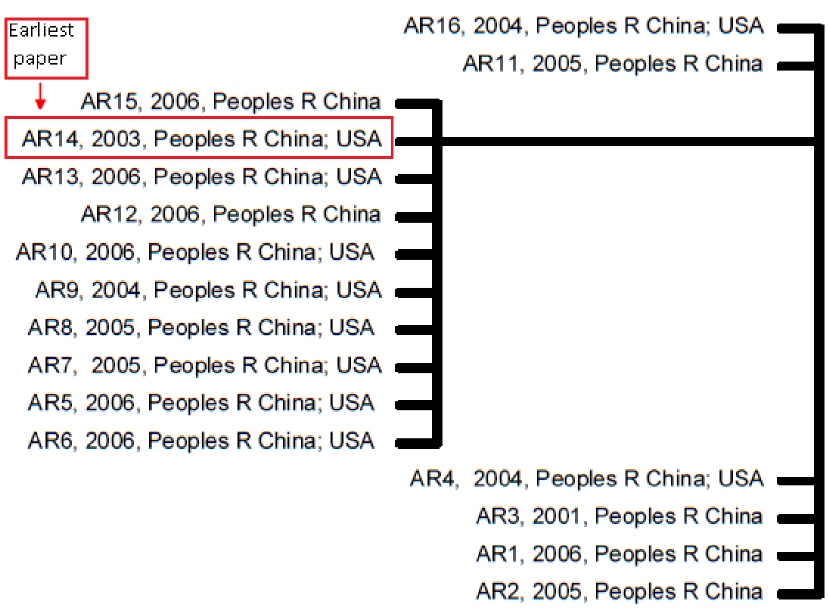
The first selected case is Zu Xiao Tao (祖小涛), a mid-career researcher at a middle- ranked university in western China. Born in 1965, Zu Xiao Tao gained his Ph.D. from Sichuan University (China) in 2002. Funded by the Chinese government, Zu visited the Department of Nuclear Engineering and Radiological Sciences at the University of Michigan as a visiting scholar from 2001 to 2006. Zu is a full professor in the School of Physical Electronics, the University of Electronic Sciences and Technology China (UESTC), Chengdu. His main research focuses on optical irradiation, nanocomposites, and intelligence structure. According to the Chinese nanotechnology database, Zu coauthored 16 papers in nanotechnology spanning from 2001 to 2006. Among them, ten (over two-thirds) were the result of a collaborative effort with scholars at the University of Michigan.

Following keyword cleaning, a matrix of 16 titles *116 keywords was generated. The clustering threshold was set at 2; that is, articles sharing two or more keywords were assumed to have the same research topic. As shown in Figure 1, seven structurally equivalent clusters emerged from the corpus of Zu Xiao Tao's publications, suggesting seven different research subjects that Zu pursued during that period. For the purpose of illustration, the dendrogram in the figure provides information for the paper code,[3] the publication year, and collaborating countries. As depicted in the figure, except for one large cluster, the other six clusters are all singletons, in which four clusters (AR1, AR2, AR3, and AR11) are Chinese domestic papers and two (AR16 and AR4) are the outcomes of U.S.-China collaboration.

A closer examination shows that these six articles pertain to different research topics. AR1 discusses a laser-induced damage mechanism, AR2 investigates hydrogen embrittlement of a Ti-Al-Zr alloy, AR3 focuses on the process of the preparation of the TiO2 nanocrystal, while AR11 explores the properties of the photoconductive UV detector. None of them share more than two keywords and were thus clustered separately (Appendix1). In the same vein, AR4 and AR16, both of which involved scholars from the United States, examined irradiation-induced martensitic transformation and the structure of Ti-Al-Zr alloy in high-temperature alkaline steam, respectively. Each of them, which also stands out as a unique research stream, is assigned a unique group given the low/no degree of shared keywords.

Zu, however, did commit to specific research reflected by the largest cluster, containing ten nanoarticles. A close inspection of the abstracts of these papers indicates that they all investigate the optical or magnetic properties of specific nanoparticles or nanocomposites. Among these ten papers, the earliest one examining the structural and magnetic characterization of CoxNi1-x nanoparticles was co-authored by Chinese scientists at Dalian University of Technology and the University of Electronic Science & Technology and U.S. scholars at the University of Michigan in 2003. Later, another nine research papers, which pertain to the same topic, include 12 additional coauthors and two additional Chinese institutions, the Chinese Academy of Science and Sichuan University (Appendix 2). In other words, by collaborating with his peers in the U.S., Dr. Zu continues his research that began as a U.S.-China collaborated paper. This provides some evidence in support of both hypotheses 1 and 2 on the impact of U.S.-China collaboration on the advancement of China's research frontier.

Figure 2: Cluster Dendrogram of the Research Streams of Zu, Xiao Tao



[3] The 16 articles were first sorted alphabetically according to title and then labeled from AR1 to AR16. The corresponding titles of the codes are shown in Appendix 1.

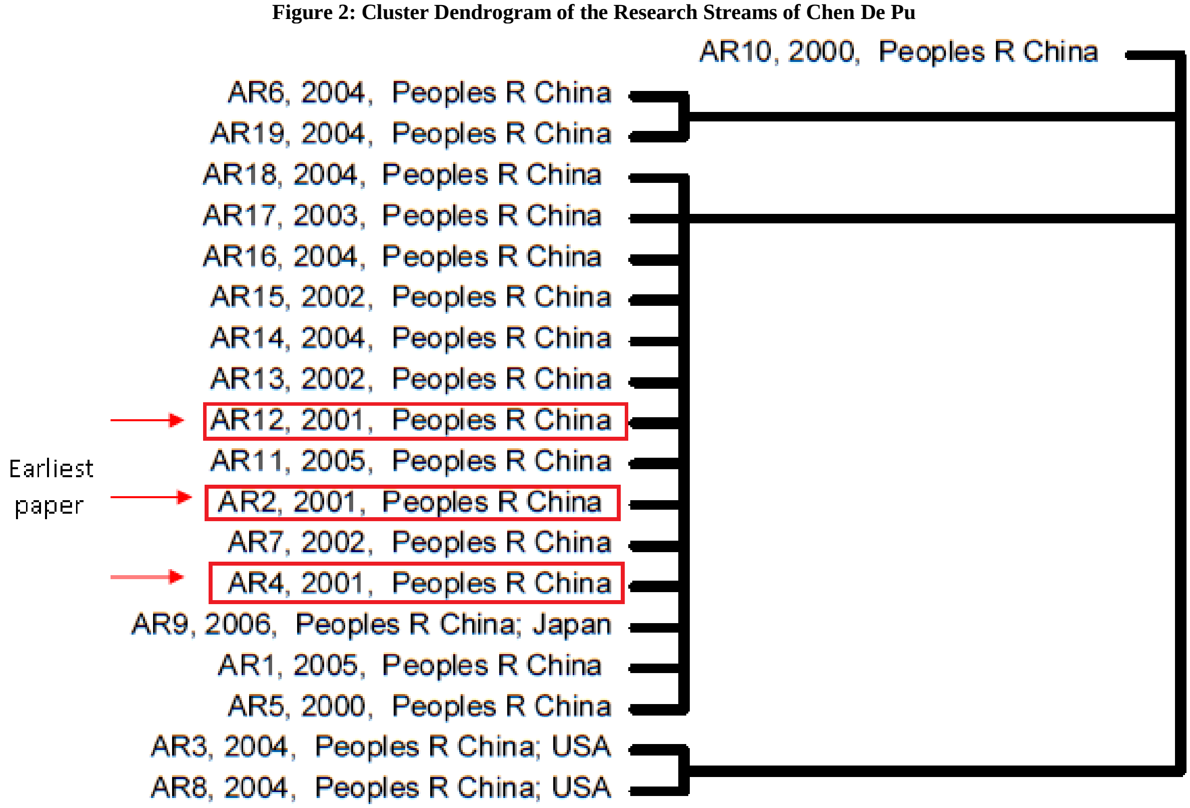
Case 2: Chen De Pu

The second selected case is Chen De Pu (陈德朴), a senior researcher in a Chinese elite university. Graduated from Tsinghua University in 1970 in chemical engineering (bachelor's degree), Dr. Chen De Pu obtained his Ph.D. in chemistry from the Chinese Academy of Sciences (CAS). From 1997 to 1999, he visited Miami University as a government-funded senior visiting scholar, and since that time, he has been a professor at Tsinghua University. His research focuses on probing the photoluminescence properties of semiconductor nanocrystals, their applications in biological fluorescent probes, and DNA purification and gene typing. According to his online curriculum vita, Dr. Chen De Pu has published more than 60 articles and filed ten patents.

Dr. Chen has authored 19 nanopapers found in the Chinese nanotechnology dataset. Two articles resulted from collaboration with colleagues in the U.S., and one involved researchers in Japan. Repeating the same analytical procedures, the matrix of 19 articles * 114 keywords was created. Running the same script, the R program produced four clusters based on the research distance reflected by keywords.

Figure 3 illustrates the four research streams that Dr. Chen has pursued in the domain of nanotechnology. One singleton cluster, AR10, describes the sol-gel process of generating alpha-Fe2O3 nanoparticles. AR6 and AR19 relate to research in x-ray lithography. The third research stream, which is also apparently Dr. Chen's primary focus, explores the structure, properties, and application of nanocrystals and various nanoparticles. In addition to research initiated in past projects, a keyword analysis also identifies a new research line in which Dr. Chen was engaged in 2004. As shown in Figure 3, the fourth cluster consists of two papers (AR3 and AR8), both of which are the outcome of U.S.-China collaboration. The abstracts reveal that these two articles investigate approaches to using magnetic nanobeads to extract genomic DNA.[4] Again, we see some evidence of the impact of U.S.-China collaboration on the increasing knowledge stock of Chinese international collaborators (H1). However, possibly due to the truncated data in both discipline and time, we could not find evidence for extended knowledge spillover (H2).

Figure 2: Cluster Dendrogram of the Research Streams of Chen De Pu



[4] The correspondence of article coding in the dendrogram and the title of the research paper is listed in Appendix 2.

Benchmarking Case

Case 3: Jiang Ya Dong

To some extent, the above two cases provide evidence in support of the influence of U.S.-China collaboration on the choice of research topics of Chinese scientists. They provide some evidence for the role of Chinese international collaborators in China's nanotechnology knowledge stock—that is, to introduce new topics manifested by both Cases 1 and 2 and to facilitate active discussion among the different parties demonstrated in Case 1. However, it remains uncertain as to whether this also holds true for all Chinese scientists. For robustness testing, a third researcher who does not have internationally collaborative articles in nanotechnology is also tested with this method.

Ideally, the benchmark case should be similar on all dimensions except the independent variable—collaborating with the U.S. or not—and the dependent variable—change of research subject and terms [34]. Thus, the benchmark case is selected based on the following three matching criteria:

1) The nano researcher did not collaborate with scholars outside of China in the period of 1990–2006 (at least as reflected in the Chinese nano dataset).

2) The researcher is affiliated with the same or similar institution as either Case 1 or Case 2.

3) The researcher has the equivalent number of publications as either Case 1 or Case 2.

4) The researcher has similar research experience as either Case 1 or Case 2.

One case, Dr. Jiang Ya Dong (蒋亚东), who satisfies the above four conditions, is identified. His online curriculum vita suggests that his research experiences are somewhat comparable to those of Xiao Tao Zu (Case 1). Born in 1964, Jiang received his Ph.D. from the University of Electronic Science and Technology of China (UESTC) in 2001, one year earlier than Xiao Tao Zu, and has worked there since. Currently a full professor at UESTC, Jiang was named a Yangtze River Scholar by the Ministry of Education of China in the field of microelectronics and solid-state electronics. Based on his online curriculum vita, he published 70 papers and applied for three patents.

The Chinese nanopublication dataset identifies 14 validated articles by Jiang Ya Dong. After the 14 titles * 52 keywords were generated, the same R script was executed and yielded only one cluster (Figure 4). This finding is in sharp contrast with that of Xiao Tao Zu, especially considering that fewer keywords lead to less likelihood of sharing. A further examination of the research content that entailed reading their abstracts showed that Jiang's articles focus on the properties, fabrication, and applications of Langmuir-Blodgett films and self-assembled polyaniline.

Figure 4: Cluster Dendrogram of Research Stream: Jiang Ya Dong

V. ANALYSIS

As mentioned, the three illustrative examples are used to demonstrate the turnover of keywords associated with international collaboration. Based on the clustering results in the dendrograms, we can observe whether or not and when an individual scientist starts publishing on topics that depart from his past field of expertise. Two alternative explanations can be advanced explaining the radical changes in research subject. One is that the departure of previous research indicates creative efforts resulting from self-learning. On the other hand, the turning point of intellectual research is possibly due to knowledge spillover resulting from the joint publishing process (integrative learning; H1). In the latter case, there also two possible scenarios: it is possible that this emergence of a research stream introduced by the U.S. coauthors to the Chinese international collaborators is digested by the Chinese scientists and diffused domestically as knowledge spillover in the joint co-publishing process. Of course, it is also likely that the false emergence of the research stream was introduced by foreign coauthors and was not picked up by Chinese coauthors. Recall Dr. Chen's research on extracting genomic DNA via nanobeads (Case 2, AR3 and AR8). This topic, which showed up in Chen's research in 2004, significantly departs from subfields in which Dr. Chen had already been active. Given time truncation, it remains uncertain whether Chen had made any new advances in that topic area or if his stream had further diffused through collaboration with Chinese domestic scholars.

It should be noted that in all three cases, even articles in the same cluster do not share the exact same keywords. As shown in the heat map (Figure 5), articles within a cluster do not have only one solid color, which not only reflects the necessity of imposing transitivity but also indicates incremental evolvement within each research stream.

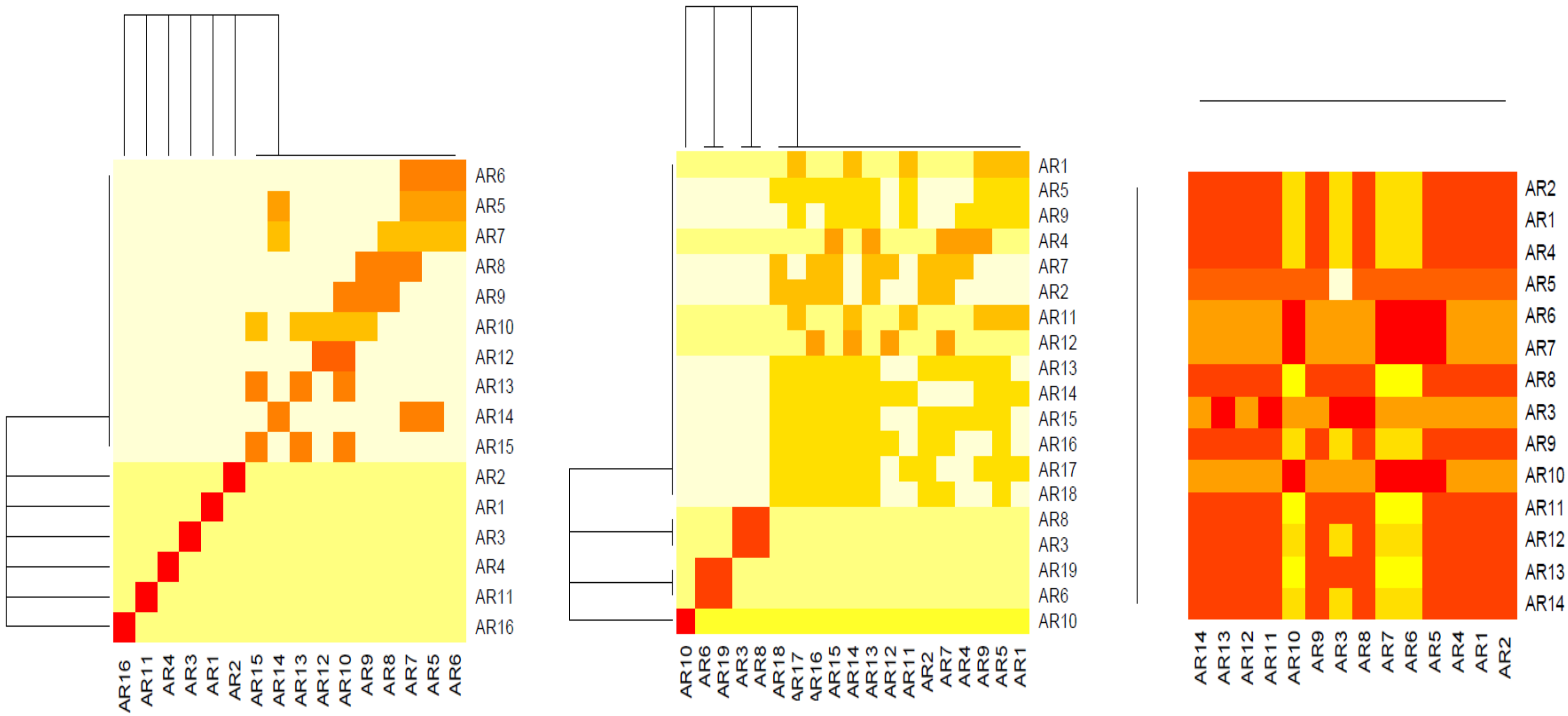
In sum, the combination of information gathered from these three cases indicates the following findings. First, the emergence of unique clusters provides some evidence that supports hypothesis 1, that U.S.-China collaboration is associated with an individual researcher's entrance into a subfield. Although three researchers, including two Chinese international collaborators and a benchmark case, all have incremental changes in their research streams, some radical changes are linked to the event of international collaboration. As reflected by all nano research taking place in China, scientific collaboration among Chinese and U.S. scientists has prompted further advancement of science in some subdomains that otherwise may not have taken place.

Figure 5: Heat Map on the Research Streams of Three Cases

Case 1: Zu Xiao Tao

Case 2: Chen De Pu

Case 3: Jiang Ya Dong (benchmark)



Second, the two cases of Chinese international collaborators show two possible scenarios taking place after Chinese researchers became involved in new lines of research with American colleagues: They could have picked up a new stream and further explored it with Chinese domestic scholars (Case 1), or such collaboration on a new subfield of investigation remained limited to only co-publishing with scholars outside of China and did not extend to domestic knowledge spillover (Case 2). Hypothesis 2 is partially supported.

Third, Cases 1 and 2 show that international collaboration enables Chinese scholars to exchange ideas and work practices with the western colleagues with whom they have worked. They provide some evidence that international collaboration makes national boundaries porous for knowledge dissemination between the U.S. and China. In addition, after visiting Chinese scholars left their American host institutions, they continued to collaborate with the researchers of their former host institutions.

VI. DISCUSSION

Findings

Knowledge creation and diffusion are increasingly being considered critical factors of national competitiveness. A widely accepted convention, albeit not tested empirically, dictates that developing countries and emerging countries have progressed very quickly through international collaboration with advanced nations. The results of this study find evidence in support of the linkage between the emergence of new research stream(s) of Chinese researchers and the event of U.S.-China collaboration. It also finds that the triggered research stream diffused further via extended coauthorship. This suggests that by collaborating with western scholars, Chinese international collaborators not only enter into the study of new sub-domains in nanotechnology but also make knowledge spillover across national borders more likely by further collaboration with other Chinese domestic scholars.

Limitations

The study has some limitations. To begin with, all publication data included in this research were those indexed in the Web of Science (WoS). However, it is the most standardized publication dataset for scientific research analysis [36, 37, and 38]. The Web of Science (WoS) publication dataset does contain bias. For one, it has a clear bias in favor of U.S. publications and strongly neglects non-English publications. In Duque's words, this is inadequate as it excludes[[?]] "…indicators of scientific productivity outside the developed world" [25]. Indeed, most Chinese scholars, similar to scholars in many other non-English-speaking countries, still publish in domestic Chinese journals, most of which are not collected by the SCI database.

This sample selection affects the analytical results of this study. To be more specific, the coverage bias of WoS suppresses the impact of international collaboration on China's knowledge stock because it is reasonable to believe that a certain proportion of co-authored papers among Chinese international collaborators and their domestic colleagues—i.e., extended collaboration following U.S.-China collaboration are invisible to WoS. Hence, if they were included, the positive impact of international collaboration would have been higher. The missing articles published in lower-level Chinese journals not indexed in WoS may conceal extended international knowledge spillover reflected by the collaboration between Chinese international collaborators and their domestic colleagues.

The second potential source of bias is introduced by two-dimensional truncated data: the time and disciplines of the publication dataset. Recall that the analyzed data in this study are nano-articles published from 1990 to 2006 and indexed in WoS. Confining the investigation to nanotechnology papers and a limited 16-year time window poses a threat to either exaggerating the direct spillover effect from Chinese international collaborators or suppressing the *indirect* spillover effects originating from them and their collaborators. This study finds some evidence to lend support to the idea that international collaboration incurs radical change rather than incremental change at the domestic collaboration level. Certainly, these three cases cannot speak to the issue of the impact of U.S.-China collaboration on Chinese scientists' research frontier since new research streams are likely to stem from Chinese international collaborators' past research prior to 1990. These limitations suggest caution in generalizing the results and the policy implications of this study, both of which are discussed below.

Contributions

Notwithstanding the above-mentioned limitations, this research has intellectual merit in the following three aspects. Past literature has not been able to adequately investigate the impact of knowledge spillover on nanotechnology development. One challenge facing this literature is the difficulty of empirically measuring spillovers. Different from the previous literature, which adopts only citation-based indicators to examine such an impact, this study also experiments with a new method of identifying the unique research stream(s) of an individual scientist and of determining if any discontinuity in the research topic is correlated with a case of international collaboration. From a methodological standpoint, it is an important step in the research evaluation domain.

Policy Implications

The findings of this project will have implications for policy. Since China's rise to power in the area of nanotechnology is uncontested, the U.S. should direct its efforts to ensuring that it has ample access to China's heavy R&D investment in this domain and that its scientists collaborate with top Chinese scientists, which is an effective way to monitor developments in science and technology in this emerging scientific powerhouse. From China's perspective, Chinese leaders should also strengthen the mechanisms that encourage collaboration with the U.S. and encourage international Chinese collaborators to establish more interactions with domestic colleagues.

It should be noted that the purpose of this paper is not intended to make a statistical generalization. However, the case of U.S.-China scientific collaboration in nanotechnology serves as a framework within which we can examine the role of international collaboration on the knowledge accumulation of a developing country. All of these experiences and lessons of China should have policy implications for other developing countries in their endeavor to catch up with advanced economies through international collaboration.

Future Research

This study warrants further exploration on refining the method of identifying the research streams and their correlation with international collaboration. This method was applied to three researchers and produced reasonably good results. For future research, the method can be refined by adding two weighting mechanisms based on the frequency of the appearance of keywords within a specific domain and the number of keywords in each article. In future work, this method can be applied to large-scale archival data to identify the evolution of research on the national level. The clustering results can also be applied to identify either domestic or international colleagues who are pursuing the same research and who may potentially collaborate on resource mobilization. Last but not least, and largely explorative, the findings drawn from the three cases presented are preliminary, and no causal relationships can be inferred. This work can also be further developed into statistical testing for generalization.

REFERENCES

[1] China Statistical Yearbook. Beijing, China: National Bureau of Statistics of P.R. China (2008).

[2] A. Hullmann, "Measuring and assessing the development of nanotechnology," *Scientometrics,* vol. 70, no. 3, pp. 739–758, 2007.

[3] L. Tang and P. Shapira, "The China-US Scientific Collaboration in Nanotechnology: Patterns and Dynamics," *Scientometrics*, vol. 88, pp. 1-16, 2011.

[4] P. Zhou and L. Leydesdorff, "The emergence of China as a leading nation in science," *Research Policy*, vol. 35, pp. 83–104, 2008.

[5] J. Youtie, P. Shapira, and A.L. Porter, "Nanotechnology publications and citations by leading countries and blocs," *Journal of Nanoparticle Research,* vol. 10, no. 6, pp. 981–986, 2008.

[6] R. P. Suttmeier, "State, self-organization, and identity in the building of Sino-U.S. cooperation in science and technology," *Asian Perspective,* vol. 32, no. 1, pp. 5–31, 2008.

[7] L. Tang and P. Shapira, "International collaboration, knowledge moderation, and the growth of China's nanoscience and nanotechnology," *Journal of Technology Management in China,* 2011, forthcoming.

[8] S. Arunachalam, R. Srinivasan and V. Raman, "International collaboration in science - participation by the Asian giants," *Scientometrics,* vol. 30, no. 1, pp. 7–22, 1994. Available from http://www.access.gpo.gov/congress/house/pdf/109hrg/21950.pdf

[9] J. S. Katz, D. Hicks, F. Narin, and K. Hamilton, "International collaboration," *Nature,* vol. 381, *no.* 6577, pp. 16, 1996.

[10] J. Qin, "An investigation of research collaboration in the sciences through the philosophical-transactions 1901–1991," *Scientometrics, vol.* 29, no. 2, pp. 219–238, 1994.

[11] European Commission. *The Third European Report on Science and Technology Indicators 2003—Towards a knowledge-based economy*. Brussels: European Commission, 2003.

[12] C. S. Wagner, and L. Leydesdorff, "Network structure, self-organization, and the growth of international collaboration in science," *Research Policy, vol. 34, no.* 10, pp. 1608–1618, 2005.

[13] J. Adams, and J. Wilsdon, “The new geography of science: UK research and international collaboration,” Evidence Ltd., 2006. Available at http://www.demos.co.uk/files/Demos_Evidence_China.pdf

[14] O. Persson, G. Melin, R. Danell, and A. Kaloudis, “Research collaboration at Nordic Universities,” *Scientometrics,* vol. 39, no. 2, pp. 209–223, 1997.

[15] A. Basu, and R. Aggarwal, “International collaboration in science in India and its impact on institutional performance,” *Scientometrics,* vol. 52, no. (3), pp. 379–394, 2001.

[16] K. Hwang, ‘International Collaboration in Multilayered Center-Periphery in the Globalization of Science and Technology,” *Science, Technology & Human Values,* vol. 33, no. 1, pp. 101-133, 2008.

[17] J. Royle, L. Coles, D. Williams, and P. Evans, “Publishing in international journals—An examination of trends in Chinese co-authorship,” *Scientometrics,* vol. 71, no. 1, pp. 59-86, 2007.

[18] C. S. Wagner, *The New Invisible College: Science for Development.* Brookings Institution Press, 2008.

[19] J. S. Katz, and B. R. Martin, “What is research collaboration?” *Research Policy,* vol. 26, no. 1, pp 1- 18, 1997.

[20] F. Narin, K. Stevens, and E. S. Whitlow, “Scientific Cooperation in Europe and the Citation of Multinationally Authored Papers,” *Scientometrics,* vol. 21, no. 3, pp. 313–323, 1991.

[21] M. Bordons, I. Gomez, M. T. Fernandez, M. A. Zulueta, and A. Mendez, “Local, domestic and international scientific collaboration in biomedical research,” *Scientometrics,* vol. 37, no. 2, pp. 279–295, 1996.

[22] F. Barjak, and S. Robinson, “International collaboration, mobility and team diversity in the life sciences: Impact on research performance,” *Social Geography Discussions,* vol. 3, pp. 121–157, 2007.

[23] Z. L. He, X. S. Geng, and C. Campbell-Hunt, “Research collaboration and research output: A longitudinal study of 65 biomedical scientists in a New Zealand university,” *Research Policy,* vol. 38, no. 2, pp. 306–317, 2009.

[24] R. Leimu, and J. Koricheva, “Does scientific collaboration increase the impact of ecological articles?” *Bioscience,* vol. 55, pp. 438–443, 2005.

[25] R. B. Duque, et al. “Collaboration paradox: Scientific productivity, the Internet, and problems of research in developing areas,” *Social Studies of Science*, vol. 35, no. 5, pp. 755–785, 2005.

[26] J. D. Adams, G. C. Black, J. R. Clemmons and P. E. Stephan, “Scientific teams and institutional collaborations: Evidence from U.S. universities 1981–1999,” *Research Policy,* vol. 34, no. 3, pp. 259–285, 2005.

[27] N. Carayol, and M. Matt, “The exploitation of complementarities in scientific production process at the laboratory level,” *Technovation,* vol. 24, no. 6, pp. 455–465, 2004.

[28] L. Tang, and J. Walsh, “Bibliometric Fingerprints: Name Disambiguation Based on Approximate Structure Equivalence of Cognitive Maps,” *Scientometrics,* vol. 84, no. 3, pp. 763-794, 2010.

[29] S. Wasserman, and K. Faust, *Social network analysis: Methods and applications*. Cambridge University Press, 1994.

[30] R. A. Hanneman, *Introduction to social network methods*. 2004.

[31] R. Pieters, H. Baumgartner, J. Vermunt, and T. Bijmolt, “Importance and similarity in the evolving citation network of the International Journal of Research in Marketing.” *International Journal of Research in Marketing,* vol. 16, no. 2, pp. 113–127, 1999.

[32] J. Zhang, C. M. Chen, and J. X. Li, “*Visualizing the intellectual structure with paper-reference matrice,”* Paper presented at the IEEE Transactions on Visualization and Computer Graphics, 2009.

[33] A. Porter, J. Youtie, P. Shapira, and D. Schoeneck, “Refining search terms for nanotechnology,” *Journal of Nanoparticle Research*, vol. 10, no. 5, pp. 715–728, 2008.

[34] A. Przeworski, and A. Teune, *The logic of comparative social inquiry*. Krieger, Malabar, 1970.

[35] A. Agrawal, and I.C.J. McHale, “Gone but not forgotten: Labor flows, knowledge spillovers, and enduring social capital” *NBER Working Paper*, 2003.

[36] S. G. Levin, and P. E. Stephan, “Sociology of science: Are the foreign born a source of strength for U.S. science?” *Science*, vol. 285, no. 5431, pp. 1213–1214, 1999.

[37] P. E. Stephan, and S. G. Levin, “Inequality in scientific performance: Adjustment for attribution and journal impact,” *Social Studies of Science*, vol. 21, pp. 351–368, 1991.

[38] L. Turner, and J. Mairesse, “Explaining individual productivity differences in scientific research productivity: How important are institutional and individual determinants? An econometric analysis of the publications of French CNRS physicists in condensed matter (1980–1997),” Unpublished manuscript, 2003.

[39] R. N. Kostoff, R. G. Koytcheff, and C. G. Y. Lau, “Structure of the nanoscience and nanotechnology applications literature,” *Journal of Technology Transfer*, vol. 33, pp. 472–484, 2008.

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